REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
12/10/10

2. REPORT TYPE
Final

3. DATES COVERED *(From - To)*
15/12/08 - 3/31/10

4. TITLE AND SUBTITLE
Wave Chaos and HPM Effects on Electronic Systems

5a. CONTRACT NUMBER

5b. GRANT NUMBER
AFOSR FA9550071049

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Antonsen, Thomas M. Jr.
Ott, Edward
Rodgers, John
Anlage, Steven M.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of Maryland
3112 Lee Bldg.
College Park MD, 20742 -5100

8. PERFORMING ORGANIZATION REPORT NUMBER
5-28035-F

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Office of Scientific Research
875 North Randolph St.
Arlington VA 22203

10. SPONSOR/MONITOR'S ACRONYM(S)
AFOSR PK-3

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-OSR-VA-TR-2012-0602

12. DISTRIBUTION/AVAILABILITY STATEMENT
Distribution A : Approved for Public Release

13. SUPPLEMENTARY NOTES

14. ABSTRACT
During the reporting period we successfully applied our Random coupling model to the study of three problems relevant to wave propagation and scattering in complicated environments. We studied the sensitivity of the reconstruction of time reversed signals to changes in the local environment. We formulated a universal model for the behavior of the time domain response of a complicated cavity to a pulse of electromagnetic energy. We elucidated the competition between direct and indirect propagation paths in the scattering of radiation within an enclosure. Furthermore, we have demonstrated good agreement between experimental measurements and large-signal circuit simulations of several upset mechanisms in complementary metal oxide transistor circuits (CMOS).

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Thomas M. Antonsen Jr.
				7	19b. TELEPHONE NUMBER *(Include area code)* 301-406-1635

Wave Chaos and HPM Effects on Electronic Systems
AFOSR FA9550071049
Final Report – T.M. Antonsen

During the reporting period we successfully applied our Random coupling model to the study of three problems relevant to wave propagation and scattering in complicated environments. We studied the sensitivity of the reconstruction of time reversed signals to changes in the local environment. We formulated a universal model for the behavior of the time domain response of a complicated cavity to a pulse of electromagnetic energy. We elucidated the competition between direct and indirect propagation paths in the scattering of radiation within an enclosure.

A. Effect of short orbits on impedance statistics

The statistical properties of the scattering of electromagnetic waves into and out of enclosures is of interest in the typical case in which precise knowledge of the configuration of the enclosure and its contents is not available. A general approach is to separate the process of coupling energy through the ports of the enclosure, which can be analyzed using first principles, from the process of excitation of the modes of the enclosure, which is treated statistically using random matrix theory, RMT.
In our past work we have shown this approach to be quite useful in describing the results of both computations and experiments so long as one considers statistics over a large enough range of frequencies. Over a narrow range of frequencies deviations between the predictions of the model for elements of the scattering matrix, and calculated or measured values were observed.

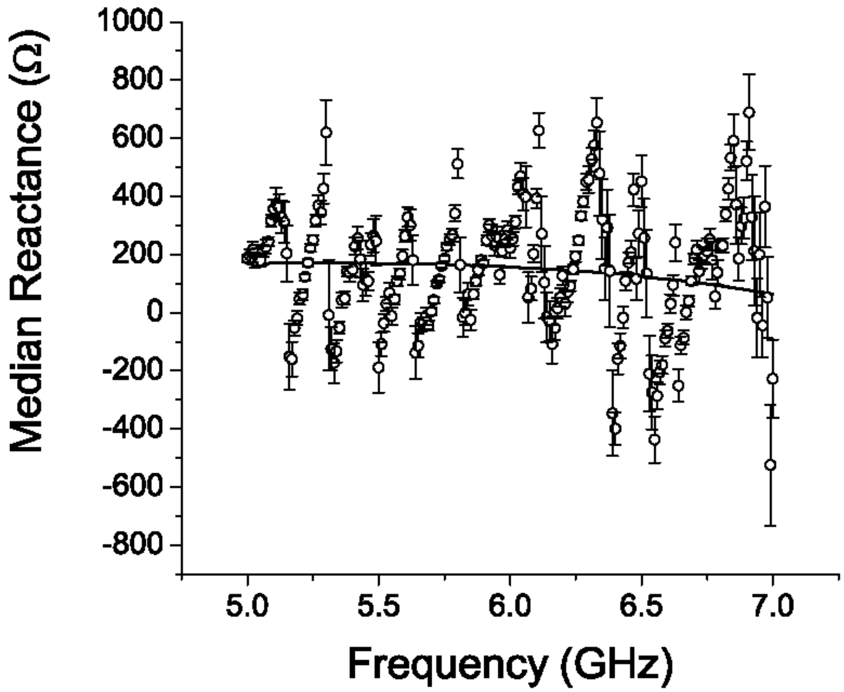
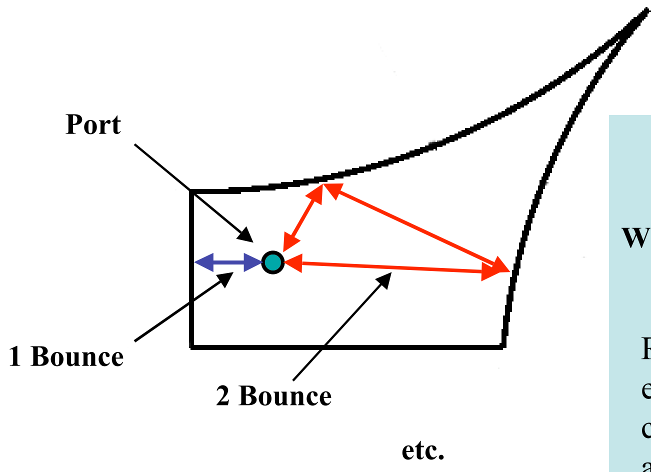


FIG. 1: A comparison between the port radiation reactance as measured by HFSS (solid line) and the ensemble median of the HFSS simulated impedances (circles), where the ensemble is generated by calculating the impedance of the cavity fro many different locations of a perfectly conducting disc placed within the cavity. The random coupling model predicts that if the ensemble is sufficiently random, the ensemble median should equal the radiation reactance. The error bars were estimated by assuming that the ensemble impedance is a Lorentzian random variable (justified by statistical examination of the ensemble data) and finding the uncertainty in the median, given the numerically found width. The differences between these two curves are caused by short orbits within the cavity which exist in many realizations of the ensemble.

In our approach the response of a cavity is described by the matrix impedance that gives the voltage at each port in terms of linear combinations of the currents at all ports. Considering the case of short wavelength and cavities whose ray trajectories are chaotic, we find that in the simplest treatment the only relevant parameters needed to make a statistical model of the cavity are the radiation impedances of the port-antennas, and the volume and quality factor of the cavity. In this case, the mean reactance measured at a port is equal to the reactance that would be measured at the port if the volume of the cavity were infinite and only outgoing waves were radiated from the port.



$$Z \;=\; j(X_{R.N} + R_{R,N}\xi)$$

Where:

$$Z_{R,N} \;=\; R_{R,N} + j\,X_{R,N}$$

Radiation impedance including the effect of <u>N-bounces</u> off the wall calculated in the <u>semi-classical approximation</u>

Semi-classical Green's function in 2D

$$G(\boldsymbol{r},\boldsymbol{r}') = \frac{1}{4}\left[H_0^{(1)}\left(k\left|\boldsymbol{r}-\boldsymbol{r}'\right|\right) + \sum_{paths-j} i\left(\frac{2}{\pi}\left|\frac{\partial^2 L_j(\boldsymbol{r},\boldsymbol{r}')}{\partial r_\perp \partial r'_\perp}\right|\right)^{1/2} \exp\left[ikL_j(\boldsymbol{r},\boldsymbol{r}') + i\pi(n-1/4)\right]\right]$$

Figure 2: The one quarter of the bow-tie shaped cavity and two short orbits that will strongly affect the impedance measured at the port. The propagation of field energy along these orbits is treated using the geometric optics propagator.

The deviations from this picture are illustrated in Fig. 1 where we show the results of many computations (using HFSS) of the reactance of an antenna radiating into a ray-chaotic cavity of the shape shown in Fig. 2. Two situations are simulated: one in which the cavity walls are perfectly absorbing, which is equivalent to radiation into free space, and one in which the cavity walls are perfectly reflecting and there is a disc shape perturber located in the cavity. For any given location of the perturber the reactance fluctuates rapidly with frequency.

The spacing between resonance frequencies is about 15 MHz, which defines the frequency scale for these rapid fluctuations. The curve plotted in Fig 1 represents the average reactance, where the average is taken over 95 different locations of the perturber. According to our original theory this average should approach the smooth reactance that is measured when the walls are perfectly absorbing. As can be seen there are systematic deviations from the expected value. The frequency scale for the deviations is 100 MHz, which is substantially greater than the mode spacing.

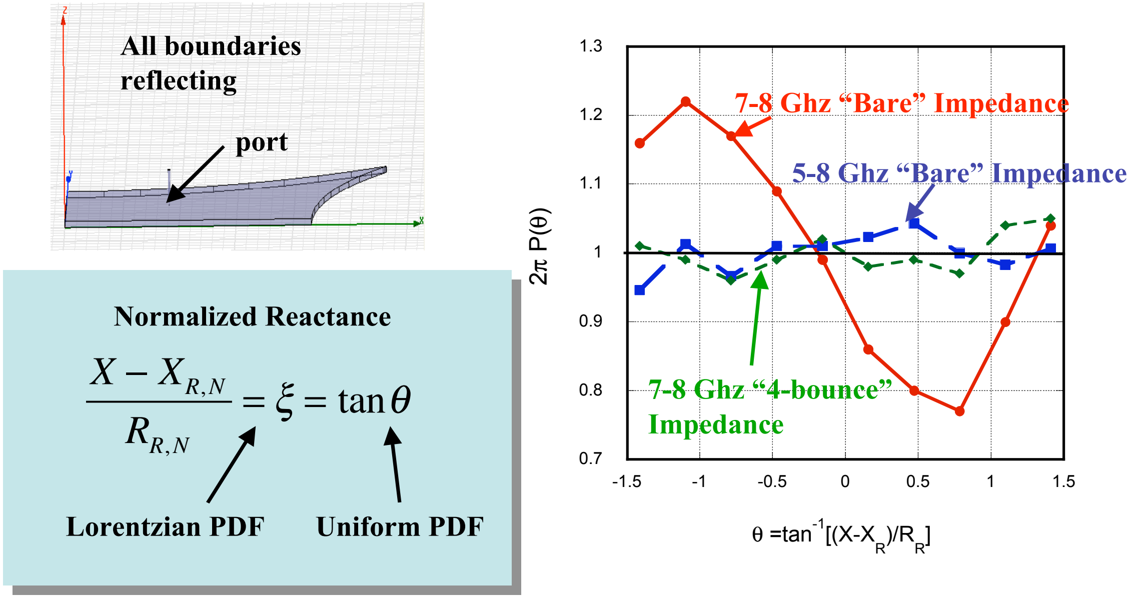


Figure 3: Test of bounce corrections to the radiation impedance

We have show that these deviations are the result of internal reflections of wave energy in the cavity that occur along relatively short ray paths starting and ending at a port. Further, we show that, with knowledge of the shortest ray paths, the statistical model can be improved substantially. Our theory is then tested by comparison with direct numerical simulations and measurements. We address the issue of short ray paths by expressing the cavity impedance in terms of a geometric optics propagator as illustrated in Fig. 2. We set as a parameter, N the number of bounces of radiation off the wall we wish to treat. We approximate the propagator as a finite unitary matrix. By assuming that it is drawn from one of Dyson's circular ensembles, we recover our previous statistics for the impedance. We then find ensembles for the propagator, which have the correct symmetries and short-trajectory corrections, but are otherwise unconstrained. From these, we calculate the impedance statistics of our cavities with short ray paths and find that they are equivalent to treating the walls and the antenna combined as a single port within a larger cavity.

The success of our approach is illustrated in Fig. 3. We calculate a large number of reactance values, X, for the bow-tie shaped cavity illustrated in the figure. We then “normalize” the reactance by subtracting the radiation reactance and dividing by the radiation resistance of the port. According to random matrix theory the result should be a Lorentzian distributed random variable ξ with zero mean and unit width, or equivalently its inverse tangent $\theta = \tan^{-1}\xi$ should be uniformly distributed. The histograms in Fig. 3 illustrate the effectiveness of our approach. If we first consider cases in which no bounce corrections are included in the calculation of the reactance and resistance used in the normalization process (i.e. the “bare” impedance is used) we see that only if samples collected over a large enough frequency range are included does the angle θ, become approximately uniformly distributed. On the other hand, if we apply the bounce

corrections to the impedance, then even reactance values collected over a narrow range exhibit the correct behavior.

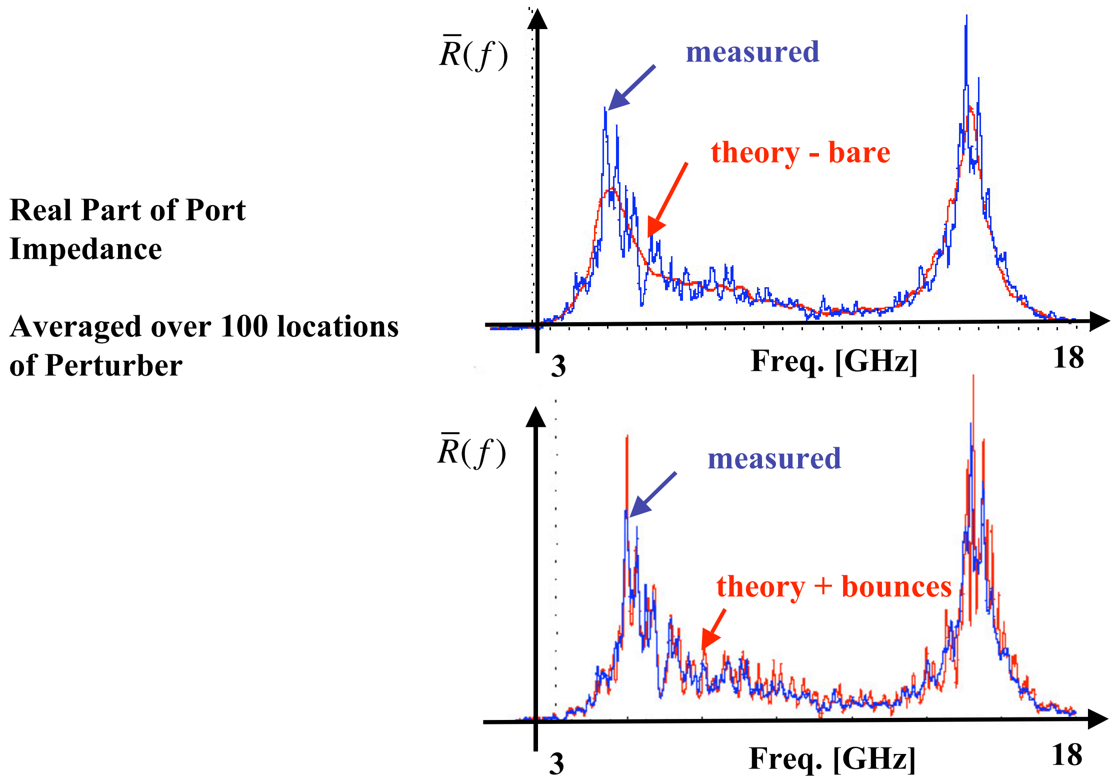


Figure 4: Comparison of predicted and measured average cavity impedance for a bow-tie shaped cavity.

The above results were obtained using data from a computation of the response of a cavity. In addition to this our experimental colleagues have measured the impedance of a real cavity and compared it with our theory. Results are shown in Fig. 4. Here the mean value of the cavity impedance is plotted versus frequency for a bow-tie shaped cavity. The mean is taken with respect to 100 locations of a perturber inside the cavity. The measured curves are then compared to the results of theory, first if there are no bounce corrections, and second if bounce corrections are included.

B. Time reversal mirror

Time-reversal symmetry of the wave equation allows one to examine several unique phenomena associated with wave physics. One of these phenomena is the time-reversal mirror (TRM). If all of the wave excitations in a system can be captured on a closed surface, and if they can be time-reversed and re-injected into the system, then the wave excitations will un-do any phase changes and distortions that they suffered in time-forward propagation. Surprisingly this phenomenon works even if only a portion of the excitations are captured. Using this fact, we have experimentally demonstrated a new electromagnetic one-recording-channel time-reversal mirror that can operate at high frequencies and high bandwidths. The experiments were carried out in a 1 m^3 ray-chaotic enclosure using two simple antennas. The input was a 7.0 GHz signal that was amplitude

modulated with a 60 ns-long pulse. The time-reversal focused signal had a peak-signal-to-noise ratio of about 9 dB, and was very sensitive to small perturbations to the ray-chaotic enclosure.

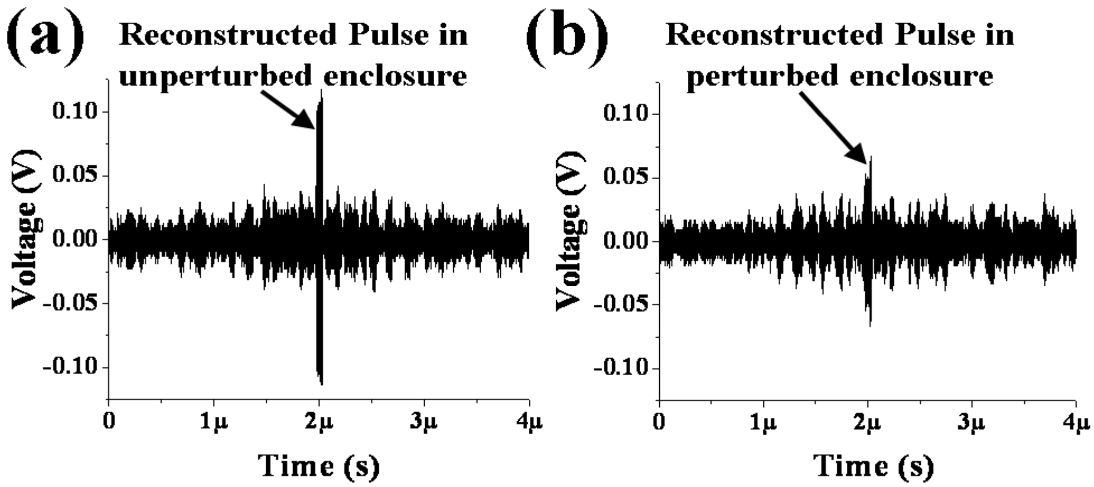


Figure 5: Reconstructed pulses in an a) unperturbed and b) perturbed cavity showing the sensitivity of the time reversal mirror to small changes in the cavity.

Publications 2009

Title: Chaotic Time-Reversed Acoustics: Sensitivity of the Loschmidt Echo to Perturbations
Author(s): Taddese BT, Johnson MD, Hart JA, et al.
Source: ACTA PHYSICA POLONICA A Volume: 116 Issue: 5 Pages: 729-732 Published: NOV 2009

Title: Effect of short ray trajectories on the scattering statistics of wave chaotic systems
Author(s): Hart JA, Antonsen TM, Ott E
Source: PHYSICAL REVIEW E Volume: 80 Issue: 4 Article Number: 041109 Part: Part 1 Published: OCT 2009

Title: Sensor based on extending the concept of fidelity to classical waves
Author(s): Taddese BT, Hart J, Antonsen TM, et al.
Source: APPLIED PHYSICS LETTERS Volume: 95 Issue: 11 Article Number: 114103 Published: SEP 14 2009

Title: Scattering a pulse from a chaotic cavity: Transitioning from algebraic to exponential decay
Author(s): Hart JA, Antonsen TM, Ott E
Source: PHYSICAL REVIEW E Volume: 79 Issue: 1 Article Number: 016208 Part: Part 2 Published: JAN 2009

Students Supported

James Hart graduated 12/2009
Jen Hao Yeh,
Ming Jer Lee,